# Assessing energy storage technology options using a multi-criteria decision analysis-based framework

Murrant, Daniel; Radcliffe, Jonathan

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# Assessing energy storage technology options using a Multi-Criteria Decision Analysis-based framework

*Daniel Murrant* and Jonathan Radcliffe*

*Birmingham Centre for Energy Storage, School of Chemical Engineering, University of Birmingham, Edgbaston, Birmingham, B15 2TT*

**Corresponding author, email: d.murrant@bham.ac.uk*

## Abstract

With the growing adoption of intermittent renewable energy generation the role for energy storage to provide a number of service needs is being increasingly recognised. However, 'energy storage' encompasses a family of technologies, each with its own set of performance, cost and physical characteristics, at different stages of development. At the same time, each energy system – however defined - has specific needs; and energy systems are themselves part of a wider socio-technical system which has aims beyond the confines of the energy 'trilemma'. As energy storage technologies develop, funding is becoming available to demonstrate their application in realistic environments. However, with multiple technical and non-technical factors to consider, it is challenging for many decision makers who often have limited expertise and resources to select which projects to support.

In this paper we first describe a novel framework for assessing the wider benefits that could come from deploying energy storage using Multi-Attribute Value Theory (MAVT), a form of Multi-Criteria Decision Analysis. We then use the framework to assess six potential energy storage projects through a combination of technical analysis and stakeholder input in the county of Cornwall in the UK: a region that has good solar and wind resource with relatively low demand and constrained network infrastructure. The projects assessed were: power to gas, a distributed battery system, battery storage integrated with solar PV and demand from Cornwall Airport Newquay, liquid air energy storage, battery storage integrated with wave energy, and thermal energy storage at a new residential development.

We conclude that MAVT can provide a straightforward and user-friendly approach, which can be easily used by decision makers for assessing energy storage projects across a range of criteria and promoting engagement with stakeholders. This approach also allows the subjectivity of decision-making, a potential limitation, to be explored through a sensitivity analysis. The use of MAVT can lead to important insights for the development of energy systems, which in this study included the importance of local priorities to decision-making.

In this case, battery storage with PV and demand from Cornwall Airport Newquay was the top-ranking project, performing well across a range of attributes including the maturity of the technology, its ability to defer grid upgrades and economic viability.

**Keywords:** Energy storage; energy system planning; multi-criteria decision analysis; multi-attribute value theory. **Declaration of interest:** none

**Glossary:**
RET; Renewable Energy Technology
ES; Energy Storage

EES; Electrical Energy Storage
TES; Thermal Energy Storage
MCDA; Multi-Criteria Decision Analysis
CC; Cornwall Council
CAN; Cornwall Airport Newquay
DNO; Distribution Network Operator
MAVT; Multi-Attribute Value Theory
MAUT; Multi-Attribute Utility Theory
AHP; Analytical Hierarchy Process

## 1. Introduction

The growing need to decarbonise economies alongside the decline in cost of renewable energy technologies (RETs) over the last two decades means that in many countries and regions RETs now meet a significant proportion of the energy demand. According to the International Energy Agency RETs provided 23% of global electrical energy demand in 2015 and this is expected to rise to 37% by 2040 [1]. Many RETs use intermittent sources (wind, solar) so generation is variable, wind and solar generation met 3% and 1% respectively of global electricity demand in 2015 and this is expected to rise to 10% and 6% by 2040 [1]. As RETs reach a greater level of grid penetration there is a need for additional balancing measures to ensure supply meets demand [2].

Energy Storage (ES) technologies are one of the principle balancing measures, allowing energy to be stored at times when generation is greater than demand, and to be supplied when generation is less than demand [3]. Electrical Energy Storage (EES) can provide a range of applications from ancillary services such as frequency response and voltage support to longer term bulk energy storage [4], [5]. Thermal Energy Storage (TES) can also provide benefits to energy systems, particularly when combined with the provision of heat or coolth, given that energy demand for heat is often larger than for electricity [6]. For example, electrical energy generated by renewables at times of low demand can be stored thermally and then used as heat or electricity at peak times [7]. Strbac et al find that “achieving deep decarbonisation at efficient cost will require a significant increase in system-wide flexibility from the current levels”; additional ES can play a key role in providing new sources of flexibility [8].

Whilst ‘energy storage’ is often referred to in general terms, there are a range of technological options available, each able to provide different energy system services across varying time and energy scales. Each technology is unique with its own technical and physical characteristics [9], so a multi-dimensional assessment must be made when considering which ES options could meet a system need. Although there are existing tools for assessing conventional energy technologies against multiple criteria, such as those described in [10] and [11], ES options present unique challenges [12] that merit specific attention. Fundamentally ES is a family of enabling technologies designed to improve the performance of a network or system rather than simply generate or deliver an energy service, this makes it more complex to identify the benefits provided.

Furthermore, there are other factors including economic, environmental and social benefits [13], such as employment opportunities [14], reduction in $CO_2$ emissions and other pollutants [15], and energy justice [16], which influence decision-makers. Despite this, commercial deployment of energy storage focuses mostly on techno-economic assessments [17], with limited consideration of the environmental and social factors [18].

Due to this multi-dimensional nature of ES options, to allow a range of views on a holistic set of factors to be considered, it is important that any assessment framework developed can be adopted by, and allows the participation of, a wide-group of decision-makers and stakeholders, many of whom operate at a local-level including local authorities, private businesses and community groups. These organisations play an important role in facilitating the transition to a sustainable energy system [19], however many have limited resources and/or technical expertise [20]. It has been acknowledged that for these reasons many decision-makers can have difficulties with models which aim to assist with decision making in complex systems such as the energy system [21]. Therefore, a framework for assessing options which is not overly complex or time consuming is required.

This paper introduces a framework based on Multi-Attribute Value Theory (MAVT), a form of Multi-Criteria Decision Analysis (MCDA), for assessing ES options. MAVT has not been used to assess ES options previously, while MCDA has been used in only a handful of instances to assess specific ES technologies, in part due to the challenges discussed above. References [22], [23], and [24] focus on how ES can be used to improve the power quality of electricity networks, [25] assesses ES options for the integration of wind power in the United States, and [26] aims to identify an ES system for a coastal town in Pakistan. In all of these cases, and indeed in most energy planning cases, the methodologies are complex and resource-heavy. Furthermore, although [25] is informed by a narrow range of expert opinion, none of the studies uses stakeholder engagement to assess the wide range of factors which can influence the decision-making process.

The framework presented in this paper is novel as it takes into account a broader set of factors than previous studies and combines technical input with a participatory process of stakeholder engagement for assessing ES options.

The participatory nature of the framework promotes engagement with stakeholders from a range of disciplines allowing a holistic set of factors related to the energy system and other relevant societal aims to be taken into account. In partnership with local stakeholders the methodology has been tested in the county of Cornwall, a rural part of the UK which has a high concentration of renewable generation and a constrained network. The strengths and weaknesses of the approach are considered, and policy insights identified as a result of the use of this framework are discussed.

## 1.1 Cornwall

Cornwall is the most south-western county in the UK, at an extremity of the national transmission network. A single 400kV line ends approximately halfway through Cornwall at Fraddon. The low-voltage distribution network is owned and operated by the Distribution Network Operator (DNO), Western Power Distribution (WPD).

Cornwall has the best solar resource [27], and one of the better wind resources in the UK [28], consequently it has a high level of grid-connected renewable generation. At the end of 2016 Cornwall had 130MW of installed wind capacity and 553MW of solar PV capacity [29], representing 1.1% and 4.6% of national capacity [30], for a county whose electricity consumption is only 0.9% of the UK total [31]. Table 1 gives a full breakdown of installed capacity and corresponding generation in Cornwall.

**Table 1 Installed capacity and electricity generation in Cornwall, (all data taken from [29], except Gas/Oil where installed capacity was taken from [30] and generation was calculated using an average load factor taken from [32])**

| Technology | Installed Capacity (MW) | Generation (GWh) |
|---|---|---|
| PV | 553 | 509 |
| Wind | 130 | 281 |
| Hydro | 0.7 | 2 |
| Landfill Gas | 14 | 83 |
| Anaerobic Digestion | 0.2 | 1 |
| Other Biomass | 1.3 | 6 |
| Municipal Waste | 26.3 | 0[1] |
| Gas/Oil | 140 | 1 |
| Total | 866 | 883 |

1. Cornwall's energy from waste plant was installed by 2016 but not operational until 2018 [33]

Figure 1 shows the estimated monthly electricity demand, and solar PV and wind generation for Cornwall in 2016. The methodology used to produce Figure 1 and Figure 2 is described in Appendix A. Figure 1 shows that local variable RET generation can meet over 40% of demand in May, June and July when solar generation is at its peak and demand is at its lowest. However, monthly data does not reveal the daily patterns in generation and demand; Figure 2 shows the hourly demand and variable RET generation for a typical weekday in June. It shows that during the daylight hours when solar generation is making a considerable contribution, local RET generation can meet a significant proportion of Cornwall's instantaneous demand, peaking at over 80% between 11am and 1pm. This is for the county as a whole and hides local variation meaning there are likely to be areas where generation supply will significantly outstrip demand. This high level of local generation contributes to an increase in congestion on the network leading to curtailment and the need for grid upgrades before new generation assets can connect to the network [34]. This situation is exacerbated by the fact that much of the grid network throughout the southwest of England is also constrained [35].

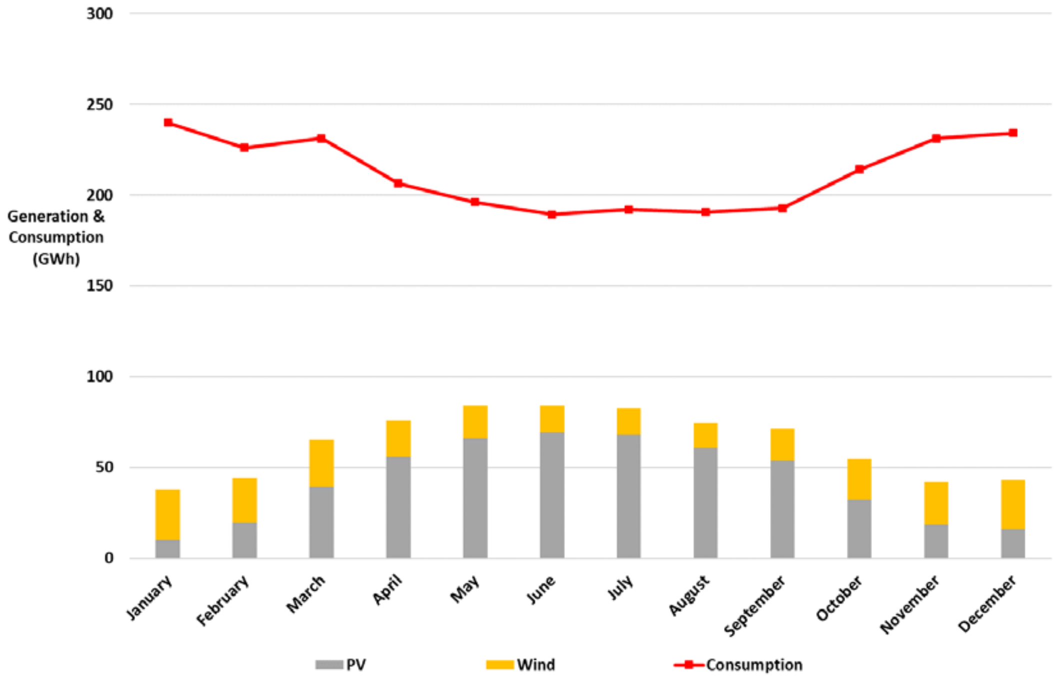


**Figure 1 Estimated monthly electricity generation and demand in Cornwall in 2016**

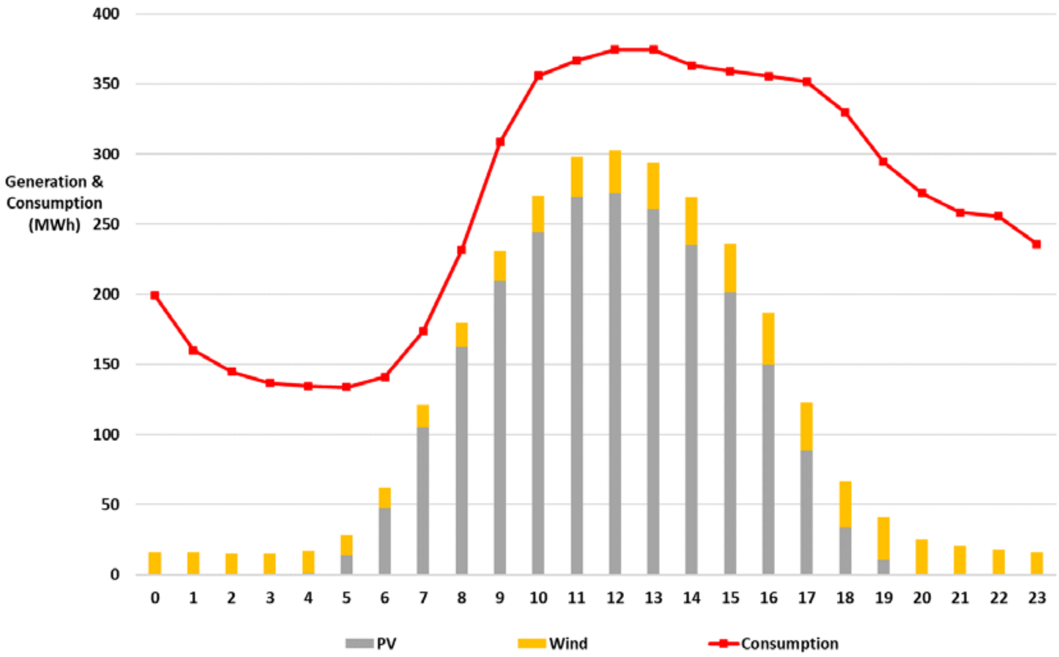


**Figure 2 Estimated daily electricity generation and demand in Cornwall during June**

In addition to electricity, heat is important to consider for a number of reasons;

- Cornwall's demand for heat energy was just over 5,000 GWh in 2010, 1.8 times that of electrical energy demand in the same year. It is forecast to remain at over 4,000 GWh by 2030 despite reduced heat consumption of new developments [36].

- Almost 50% of Cornwall's homes are off the main gas network and therefore rely on more expensive forms of heating (over 3 times the national average), including from fuel oil and electricity [37].
- 35% of Cornwall's homes are solid wall properties and so are difficult to retrofit with heat efficiency measures [37].
- Fuel poverty in Cornwall is in the highest quartile of English counties with 12.8% of households effected compared to a national average of 11.1% [38].
- Almost 400 estimated excess winter deaths occur in Cornwall each year [39].

Figure 3 shows the estimated monthly gas demand which can be used as a proxy for heat demand for Cornwall in 2016. Cornwall's annual gas demand of 2,434GWh [40], was assumed to follow the same monthly profile as the UK as a whole [41]. The seasonal variability will become increasingly important with electrification of the heat sector as part of a decarbonisation strategy [42].

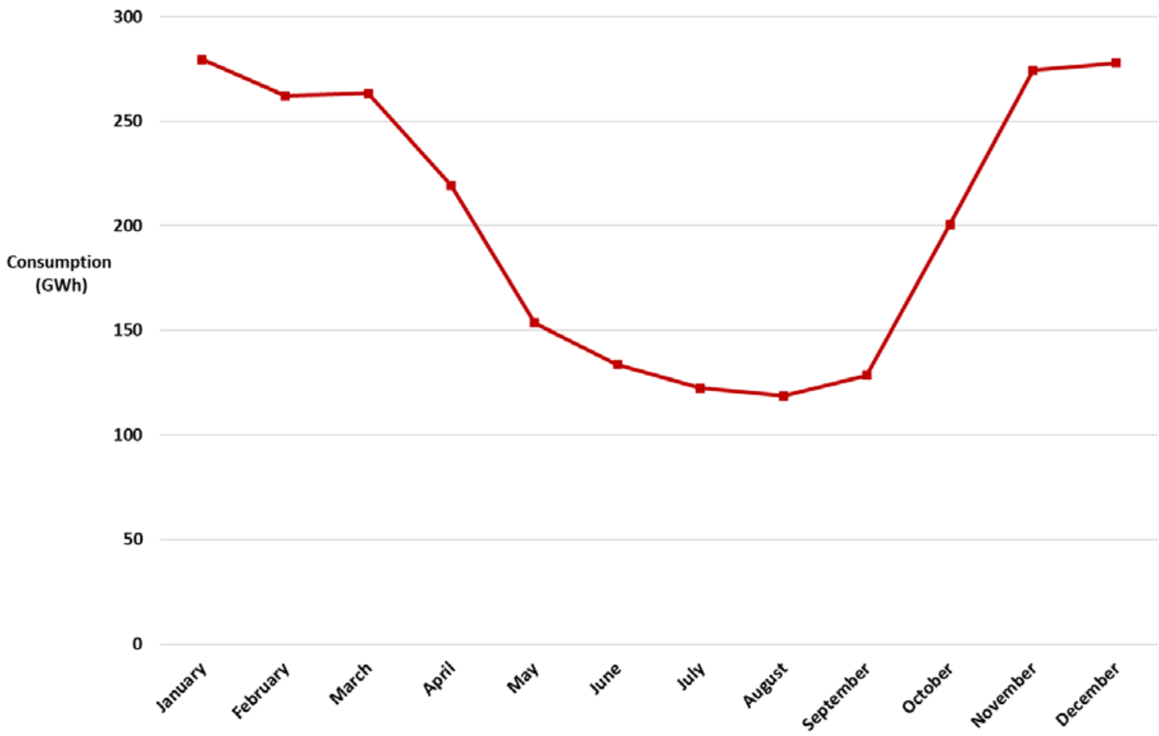


**Figure 3 Estimated monthly gas demand in Cornwall in 2016**

In 2017 Cornwall Council (CC); Cornwall's Local Authority, approved the 'Vision for Cornwall's Energy future' which included a target for 100% of Cornwall's electricity demand to be met by renewable and low carbon sources by 2030 [43]. From the data shown in Table 1 and Figure 1, RET generation produced 882GWh of Cornwall's total annual demand of 2,545GWh, so to meet this target, assuming the ratio of RET technologies remains the same would require a 2.9x increase in capacity resulting in 1,600MW of solar PV and 380MW of wind. Furthermore to meet this target is it likely a larger proportion of solar PV will be required given the current negative policy landscape for onshore wind in the UK [44].

CC has a devolution deal with the UK government which includes energy [45]. The deal includes an implementation plan to deliver a smart ES demonstrator [45]. Subsequently CC commissioned Encraft and the Birmingham Centre for Energy Storage to produce an Energy System and Storage

Masterplan for Cornwall (referred to as the Masterplan) [46]. One objective of the masterplan was to identify a prioritised list of possible ES projects for Cornwall which could potentially be implemented by CC. This paper will describe how the MCDA-based approach was used to develop this list for the Masterplan, and expand on the results produced in the Masterplan by carrying out a sensitivity analysis.

### 1.2 Multi-criteria decision analysis

When policy makers are developing strategies to solve problems or achieve long term goals there are usually multiple objectives that need to be met, and therefore multiple criteria that have to be traded-off against each other [47]. MCDA is an umbrella term for a number of techniques that allow the ranking or prioritisation of options; each option will not satisfy all the criteria to the same extent but those options ranked the highest are judged to provide the greatest net benefit [48]. An essential part of this process is the weighting of criteria as it is important to recognise that achieving different criteria has different value to stakeholders.

MCDA has been used to prioritise options across a number of sectors including healthcare [49], finance [50], and natural resource management [51]. MCDA has also been used to aid in the development of sustainable energy systems [52], and radioactive waste management [53]. As discussed in section 1, although MCDA has been used in a handful of instances to assess specific ES options these approaches have been complex, considered a narrow range of assessment factors and lacked stakeholder engagement. Furthermore, a review of the literature finds that MAVT itself has not been used to assess ES options.

There are many ways to classify MCDA techniques; one approach discussed in several articles including [47], [54] and [55], separates these techniques into three broad categories: Value Measurement models; Goal Programming, Aspiration and Reference Level models; and Outranking models. These are described below.

Value Measurement models assign a numerical score to each option being assessed providing a ranking of the options in order of preference [51]. Each criterion is given a weighting reflecting its partial contribution to the final numerical score, these weightings should represent the level of trade-off the decision maker is prepared to make between the criteria [56]. Compared to the other MCDA techniques, Value Measurement Models are often less mathematically complex methods [57], and so are easy to understand and use, as well as being easy to present visually [55]. The main limitation is the relative subjectivity in determining the weightings and assessing the criteria [58].

Goal Programming, Aspiration and Reference Level methods are three similar MCDA approaches which are commonly grouped together and referred to as 'goal programming' [47]. Goal programming sets desirable goals or aspirations for each criterion, and then identifies the options which come closest to achieving these [51]. Goal programming can be less subjective than value measurement models though it has several weaknesses including challenges around weighting the aspirations selected, which is important for normalising the aspirations and factoring in their relative importance [59]. Furthermore significant computational time is required to produce results which even then are difficult to represent visually [55].

Outranking models initially compare two or more options to identify which is preferred in respect of each criterion. The comparisons in respect of each criterion are then aggregated to determine which option performs best against the most criteria and so should be favoured for selection [60].

Outranking models are most suitable when criteria metrics are not easily aggregated [60], although they tend to be used as part of an initial screening process to identify a short list of options [56], rather than to finally identify the most appropriate option [47]. A key weakness of outranking models is the relatively complex nature of the algorithms employed [61], meaning users are limited to experts [57].

All three techniques have been used to prioritise options within the energy sector; Goal Programming and Outranking models have both been used for energy planning studies such as for assessing the environmental impact of energy generation options or evaluating alternative electricity supply strategies [47]. Although Value Measurement models have been used for these type of studies they have especially been used for ranking specific energy generation technologies [47]. This, along with their ease of use, which will be important if this approach is to be widely employed by local-level actors and engaged with by a variety of stakeholders, makes Value Measurement models particularly appropriate for assessing ES technologies.

Within the category of Value Measurement models there are three individual techniques which are commonly used, although not for assessing ES options; Multi-Attribute Value Theory (MAVT), Multi-Attribute Utility Theory (MAUT) and the Analytical Hierarchy Process (AHP). MAVT is the least mathematically complex, and most accessible technique, but due to the weighted nature of the attributes still provides value to decision-makers when trying to trade-off the respective, multi-dimensional benefits of specific technology options. MAUT is generally seen as an extension of MAVT but with a more complex methodology to allow risk preferences and uncertainty to be accounted for [47]. AHP has several similarities to MAVT and MAUT but uses pair-wise comparisons to both compare options against the relevant criteria and to estimate criteria weightings [54]. One key disadvantage of AHP is that it can be very time consuming when the number of options and/or criteria are large which could be the case when considering ES technologies [59].

Both [62] and [51] that when using MCDA techniques the quality of the implementation of the analysis is more important than the specific technique used. Consequently, and given that an ambition of the present study was to allow the framework proposed to be used by a wide group of decision makers, MAVT was chosen due to its relatively uncomplicated nature and wide accessibility. As discussed in section 1, it is important to maximise the benefit this framework has to local-level actors and to promote a wide range of stakeholder engagement.

# 2. Methodology

## 2.1 Multi-Attribute Value Theory

Fundamentally MAVT allows multiple options to be assessed against several criteria, usually referred to as attributes. Each option is given a score, known as a partial value function, for how well it meets each attribute; and each attribute is given a weighting to reflect its importance to meeting a predefined goal. The total for each option is the sum of the products of the partial value function and weighting for each attribute. The option with the highest total value is judged to be the one which provides the greatest net benefit.

Mathematically a total value (V) is assigned to each option being considered, where the options are defined as a, b, c…. . Therefore for n attributes defined by i,

$$V(a) = \sum_{i=1}^{n} w_i v_i(a)$$

where $v_i(a)$ is a partial value function and reflects options a's rating for attribute *i*, and $w_i$ is the weighting given to attribute *i* to reflect its importance compared to other attributes considered [63]. Both the weightings and partial value functions are normalised to a scale, for example, 0 - 10. Figure 4 shows an example matrix used to produce an MAVT analysis.

MAVT is a relatively simple MCDA technique however its value is dependent on the attributes chosen and the process for assigning scores (the partial value function) and attribute weightings. This process as it has been applied in Cornwall to assess ES project options, combined technical analysis with stakeholder engagement, through structured workshops and follow-up questions and is detailed below.

The MAVT process for assessing ES was split into four steps;

1. Identify ES projects to be considered;
2. Establish the attributes against which these projects will be assessed;
3. Determine the weightings and partial value functions;
4. Calculate totals.

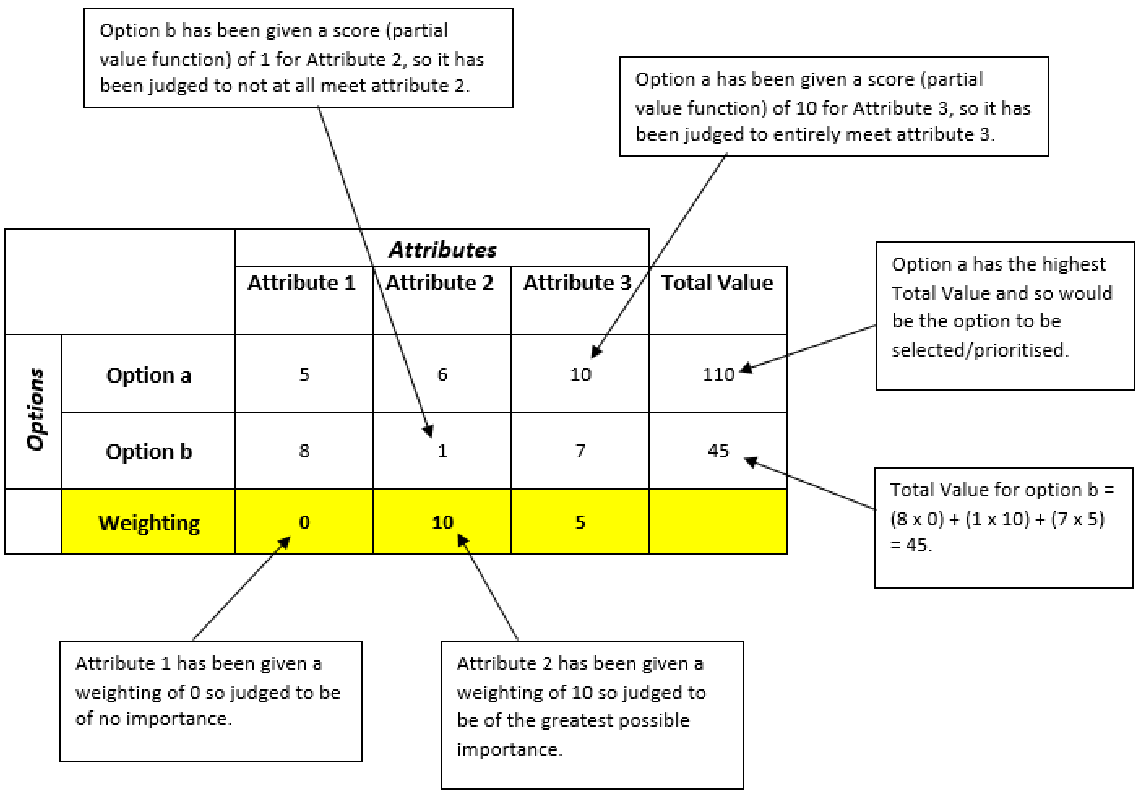


**Figure 4 Example MAVT matrix**

## 2.2 Identifying ES projects

The ES projects to be assessed and the methodology used to identify them was taken directly from the Masterplan and is detailed in that document, although a summary is provided here [46]. As with many assessments of this type, the potential ES projects were identified initially on technical

| Site Name | Type of ES | Description |
|---|---|---|
| Power to Gas, Grampound Road | Electrical (Power to Gas) | 12MW electrolyser system. |
| Virtual battery | Electrical | 5MW (10MWh) ‘virtual’ Lithium Ion |

grounds, but with a secondary aim to include a variety of technology options to provide CC with multiple options. First, potential locations for EES were identified by correlating areas where generation exceeded demand with constrained points of the distribution network in Cornwall [64].

Secondly, ES technologies (EES and TES) were reviewed, covering technological maturity, technical performance, and the services they could provide. This allowed specific technologies to be selected for the priority areas. These projects are summarised in Table 2, while Figure 5 shows the location of the EES projects selected. Unlike the other projects considered in this paper the TES project is not site specific but on the request of CC could be sited in any new development in Cornwall. A more detailed description of each project is provided in Appendix B, drawn from the Masterplan [46]. To demonstrate the range of different storage solutions available to Cornwall and so provide CC with several viable storage solutions as per the Masterplan objective, the project options cover technologies that could be tested and provide a clear service required at the sites selected.

**Table 2 Potential ES projects in Cornwall**

| | | |
|---|---|---|
| system, North Cornwall | | battery system consisting of many domestic scale batteries. |
| Battery storage, Cornwall Airport Newquay (CAN) | Electrical | 5MW (5MWh) storage to increase CAN consumption from Kernow Solar Park. Electric vehicle storage is also considered. |
| LAES, Davidstow | Electrical | 5MW (15MWh) Liquid air energy storage at Davidstow Cheese Factory. |
| Battery storage, Wave Hub | Electrical | 5MW (5MWh) Lithium Ion battery system. |
| Residential new build – no specific site | Thermal | 2,000MWh or 4,600MWh thermal pit storage system (depending on system chosen). |

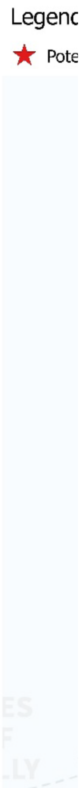

**Figure 5 Location of EES projects, (project data taken from [65], mapping data taken from [46])**

## 2.3 Establishing attributes

Before attributes can be established it is important to understand the overall objectives of the exercise. As described by CC the broad aim of the Masterplan was to identify and describe electricity network constraints in Cornwall and the impact a constrained network is having, and may continue to have, on economic growth and strategic priorities in Cornwall. Of specific relevance to this study the Masterplan had an objective to provide a list of energy storage solutions to Cornwall’s network constraints, prioritised by a series of measures including; quantified benefits, deliverability, costs, funding, utilisation and strategic importance. These measures are broad and loosely defined so it was agreed with CC that stakeholder engagement would play a key role in defining the attributes by which (through the MAVT process) the energy storage projects would be assessed. This follows one of several recognised approaches to establishing attributes for MAVT where they act as proxies and are only indirectly linked to the objective [66].

Two stakeholder workshops were held to inform the work carried out for the Masterplan, including the MAVT analysis. The workshops were attended by key energy sector stakeholders covering local and national businesses, academia, community energy groups and CC. A summary of the stakeholders who attended is given in Table 3.

**Table 3 Workshop summary**

| Workshop1: | |
|---|---|
| **Sector** | **Number of Stakeholders** |
| Academia | 3 |
| CC | 3 |
| Community Energy Groups/Social Enterprises | 3 |
| Utilities/DNO's | 2 |
| Trade Association/Union | 0 |
| Other Business/Industry | 7 |
| Total | 18 |
| Workshop 2: | |
| **Sector** | **Number of Stakeholders** |
| Academia | 0 |
| CC | 3 |
| Community Energy Groups/Social Enterprises | 2 |
| Utilities/DNO's | 3 |
| Trade Association/Union | 1 |
| Other Business/Industry | 4 |
| Total | 13 |

In the first stakeholder workshop to inform the attributes against which the energy storage projects would be judged, two key questions were posed for round-table group discussion:

Q1: What are the priorities for the energy system in Cornwall over the next 5/10/20 years?

Q2: What are the barriers to ES?

Q1 was chosen to ensure that the attributes selected were in line with Cornwall's priorities and so any projects which met them would be of strategic importance. While Q2 was used to ensure that any project which was prioritised would be realisable and not have to overcome unrealistic barriers. The feedback received to Q1 and Q2 was collated post-workshop and then reviewed to identify attributes which related to energy storage options and reflected the priorities and barriers reported. These attributes were then reviewed and confirmed first by CC, and then the stakeholders at the second workshop.

Table 4 shows the attributes, a summary of the key points from the feedback which led to a specific attribute being identified (alongside the question number the feedback related to), and the justification for identifying the attribute from the feedback given.

**Table 4 Attributes identified from stakeholder feedback**

| Attribute | Summary of feedback | Justification for Attribute |
|---|---|---|
| Deferral of grid upgrades | Alleviating or managing constraints on the network to allow greater deployment of renewable generation is crucial. (Q1). | Managing constraints by adding energy storage to the network will allow grid upgrades to be deferred. |
| | Currently there is limited data regarding where the distribution network is constrained and therefore where storage is most needed. (Q2). | |
| Economic co-benefits | A clear priority should be to explain and demonstrate real community benefits from energy storage. This is vital to their success and might include explaining the benefits of Smart Meters. (Q1). | Benefits from energy storage are likely to be in part economic, especially in the case of keeping financing local. |
| | The financing of energy storage should be local to keep benefits within Cornwall. (Q1). | |
| Economic growth (innovation) | A clear priority should be to explain and demonstrate real community benefits from energy storage. This is vital to their success and might include explaining the benefits of Smart Meters. (Q1). | Additional economic benefits from energy storage may come through innovation such as in the case of smart meters. |
| Economic viability | There is uncertainty around future energy storage revenue streams. (Q2). | Lack of revenue streams and difficulties in putting together business cases are issues which can affect economic viability. |
| | The barriers to sharing data on energy consumption make it more difficult to put together a business case for storage. (Q2). | |
| Environmental co-benefits | Alleviating or managing constraints on the network to allow greater deployment of renewable generation is crucial. (Q1). | Increasing the deployment of renewable generation has environmental co-benefits, e.g. decarbonisation, reduction in air pollution. |
| Increasing self-consumption | There should be an effort to increase consumption of electricity [generated] within Cornwall rather than continuously exporting it out of the county. (Q1). | Reducing electricity exports and increasing adoption of electric vehicles will contribute to increasing self-consumption. |
| | A push for greater adoption of electric vehicles is one way to increase self-consumption. (Q1). | |
| Technology viability | There are still significant technology barriers to energy storage; costs are currently prohibitive and some storage projects are largely unproven at scale. (Q2). | Technology barriers including a satisfactory ratio of energy delivered against energy invested are issues which can affect technology viability. |
| | Energy storage options must make sense in terms of energy delivered against energy invested. (Q2). | |

## 2.4 Determining Attribute Weights and Partial Value Functions

Both the weightings and partial functions need to be normalised before they can be used in MAVT. There are a number of techniques for doing this which are summarised by [66] and discussed in more detail by [67] and [68]; these include, rating, pair-wise comparison and qualitative translation for weightings, and direct rating, curve fitting and parameter estimation for partial functions. For this study rating/direct rating techniques were used; whereby the values are simply estimated relative to each other based on the knowledge and expertise of those providing the ratings. This represented a trade-off as these rating techniques are particularly susceptible to the views of those providing the ratings especially in the case of weightings [52]. However this technique represents the simplest and therefore most accessible approach to identifying partial functions and weightings and has been found to produce the most consistent and accurate judgements [69]. Consequently, given the need for a practical decision-making approach it was felt to be the most suitable technique for this analysis, although the impact of subjectivity will be investigated through a sensitivity analysis in section 3.4.

Partial value functions and weightings were assigned from the second stakeholder workshop. Initial values for both were provided by the authors, based on technical analysis carried out as part of the Masterplan project comprising an extensive review of literature on ES technologies including studies on both EES [70] and TES [71], and future projections of technology development [72], and analysis of Cornwall's energy system (summarised in section 1.1). These were presented to stakeholders (including representatives from CC), and the opportunity was given for amendments to be made which resulted in several changes to the partial functions and attribute weightings.

# 3. Results

## 3.1 Attribute Weightings

Table 5 shows the attributes and their final attribute weightings produced through the process described in section 2.4. The rationale for each weighting given is also shown in Table 5. 'Economic Viability' received the highest weighting of 9, as without access to project funding a project would not proceed. 'Environmental Co-benefits' received the lowest weighting of 3, reflecting how the environmental benefits of ES are largely related to their role in displacing the use of fossil-fuel generation [73],  of which Cornwall has very low levels (see Table 1),.

**Table 5 MAVT attributes and their weightings**

| Attribute | Attribute Definition | Weighting | Rationale of Weighting |
|---|---|---|---|
| Deferral of Grid Upgrades | The ability of the project to defer upgrades to the electricity network (distribution or transmission). | 8 | Deferring expensive grid upgrades was seen as one of the main drivers for ES in Cornwall and so was given a high weighting. |
| Economic Co-benefits | Economic benefits to the owner/host of the project as a result of the ES project. | 4 | Any wider economic benefits (away from direct income from the ES project) which ES could bring to the owner/host of a project were felt to be important in justifying the project. However they were not felt to be a key attribute for ES and so were given a relatively low weighting. |
| Economic Growth (Innovation) | The ability of the project to stimulate economic growth through innovation within the region. | 6 | Promoting economic growth in Cornwall was felt to be important but it was not considered to be the main role of ES and so was given a mid-level weighting. |
| Economic Viability | The ability of the project to secure funding, usually dependent on the economic profitability of the project. | 9 | Without access to funding a project would not proceed so the highest weighting was attached to this. |
| Environmental Co-benefits | Environmental benefits as a result of the ES project, such as improved local air quality. | 3 | The environmental benefits of ES are largely related to their role in displacing the use of fossil-fuel generation of which Cornwall has very low levels, so the benefits at a local |

| | | | |
|---|---|---|---|
| | | | level are relatively small. |
| Increasing Self Consumption | The ability of the project to increase the self-consumption of energy generated in Cornwall rather than relying on exports. | 6 | Increasing energy self-consumption was felt to be beneficial as it would decrease energy losses by reducing transmission distance, help retain more of Cornwall's 'energy capital' within the county and reduce congestion upstream in the electricity network. However it was not considered to be the main role of ES and so was given a mid-level weighting. |
| Technology Viability | The ability of the technology to perform as required over the lifetime of the project. | 8 | The viability of the technology will dictate its ability to perform as required and so was felt to be important. |

## 3.2 Multi-Attribute Value Theory Partial Value Functions and Final Results

Table 6 shows the weightings and partial value functions for the MAVT analysis undertaken based on the feedback obtained from the two stakeholder workshops, while Table 7 then shows the final totals of the MAVT analysis carried out.

**Table 6 MAVT weightings and partial value functions**

| | **Deferral of Grid Upgrades** | **Technology Viability** | **Economic Viability of Technology** | **Increasing Self Consumption** | **Economic Growth (Innovation)** | **Environmental Co-benefits** | **Economic Co-benefits** |
|---|---|---|---|---|---|---|---|
| ***Weighting*** | ***8*** | ***8*** | ***9*** | ***6*** | ***6*** | ***3*** | ***4*** |
| **Power to Gas (Grampound Road)** | 8 | 4 | 2 | 8 | 6 | 7 | 6 |
| **Virtual Battery System (Launceston)** | 6 | 7 | 5 | 7 | 5 | 5 | 6 |
| **Battery Storage (Cornwall Airport Newquay)** | 7 | 8 | 7 | 6 | 7 | 7 | 7 |
| **Liquid Air Energy Storage (Davidstow)** | 6 | 6 | 5 | 6 | 4 | 5 | 7 |
| **Battery Storage (Wave Hub)** | 5 | 8 | 6 | 5 | 4 | 6 | 5 |
| **Thermal Storage** | 7 | 7 | 6 | 8 | 4 | 6 | 6 |

**Table 7 MAVT final results**

| **Project** | **Total** |
|---|---|
| Battery Storage (Cornwall Airport Newquay) | 310 |

| | |
|---|---|
| Thermal Storage | 280 |
| Virtual Battery System (Launceston) | 260 |
| Battery Storage (Wave Hub) | 250 |
| Liquid Air Energy Storage (Davidstow) | 244 |
| Power to Gas (Grampound Road) | 243 |

The battery storage system at Cornwall Airport Newquay (CAN) received high partial value functions for most attributes, resulting in the highest total score; it was considered to be the most viable both from a technology and economic point. It was also judged to contribute significantly to deferring grid upgrades as it would free capacity on the distribution network, and to provide significant environmental benefits as it would remove the need for backup diesel generation at the airport.

More generally, airports provide good opportunities for ES some of which have already been considered [74]. There are several reasons for this; the environmental impacts of the aviation industry are well documented, so the industry has implemented a number of measures to reduce emissions and lessen its environmental impact including the adoption of RETs [75]. Furthermore, airports are good places to host RET and ES facilities as they tend to consume high levels of energy all day and all year round and normally have space for renewable facilities. Therefore, when decision makers are identifying ES strategies they should, where appropriate, consider airports as potential early adopters.

The TES project considered in this paper also generally received high partial value functions, particularly for the viability of the technology and its ability to defer grid upgrades and increase self-consumption (as it reduces the need of grid electricity or imported gas for producing heat). Although it received a low partial value function for Economic Growth (Innovation), as thermal storage technologies are a low priority for innovation funding in the UK [76]. Nevertheless, the mainly high partial value functions resulted in the second largest total score. This suggests that TES technologies can provide at least as many benefits as EES options. Whilst TES is receiving an ever-increasing level of commercial [77], and academic attention [78], within the UK policy makers have paid limited attention to developing TES strategies [79]. Therefore, this paper suggests that when considering ES projects policy makers must ensure TES projects are considered and not automatically overlooked in favour of EES options. This is particularly so for the UK where heating makes up just under 50% of the total energy demand [80].

The virtual battery system scored highest of the remaining options, followed by battery storage (Wave Hub), Liquid air energy storage and then the power to gas system. The main attribute which lowered the score of the virtual battery system was its economic viability, this attribute has a high weighting so a low partial-value function can have a significant impact on the total score. Economic viability was considered to be relatively low because one of the key markets to provide the revenue stream for this system; domestic users benefitting from time-of-use tariffs is still developing. However the number of time-of-use tariffs in the UK is expected to increase over the coming years [81], and so the economic viability and therefore the total score of this project may then increase.

Battery storage at the Wave Hub generally did not score as well as the projects ranked above it but it was low scores for deferral of grid upgrades and increasing self-consumption which particularly lowered its total score. This was mainly down to the location at the Wave Hub, a test centre for marine energy devices (see Appendix B, Section 1.5). The ability of the system to defer grid upgrades and increase self-consumption is linked to the levels of local RET generation which in this case is heavily dependent on the levels of marine generation being provided at the site. As marine energy is still a developing technology, this is often zero or at a very low level, however in the future as marine generation improves there is significant potential for the system to defer grid upgrades and increase self-consumption.

Liquid air energy storage scored relatively low across the board, this is largely due to its status as the least commercially mature of the technologies received, although this does leave potential to develop (since the study was undertaken a 5MW pre-commercial demonstrator has begun operating [82]). A Power to Gas system at Grampound Road received low partial value functions for technology and economic viability; these attributes were given high weightings so this will have a significant effect on the total score. This power to gas system focussed specifically on injecting hydrogen into the gas network, another option would be to use the hydrogen to power vehicles. This was outside the scope of the masterplan study, nevertheless it is an option which should be given further consideration.

When reviewing the results in Table 7 it should be noted that the projects were assessed on their current characteristics. Although all technologies considered were felt to be at least at the demonstrator stage, they are all at different levels of development which has an impact on the scores they receive. This was most noticeable in the case of Liquid Air Energy Storage, which as already discussed was the least commercially mature of the technologies assessed. As many of the technologies develop, (or in the case of the Wave Hub marine generation develops) it is likely that the scores received by projects would alter, highlighting the need to undertake an MAVT analysis as and when support or investment is being considered.

## 3.3 Sensitivity Analysis

As discussed in Sections 1.2 and 2.4 a limitation of the MAVT approach used is the subjective nature of the inputs used, particularly the attribute weightings. Therefore, it is appropriate to undertake a sensitivity analysis to assess how changing the weightings may impact the results produced. In many techno-economic models, including those relating to energy, the subjectivity is hidden [83], whereas the explicit nature of the weightings and partial value functions used in this approach allows the impact of subjectivity to be easily explored. To do this a methodology used in the peer-reviewed studies [63] and [66] which use MCDA to assess management options related to historical assets, was carried out.

This involved carrying out the MAVT analysis seven times, each time the weighting of one attribute was changed to 40% of the sum of all the existing weights shown in Table 6 (i.e. 40% of 44), while the weights of the other six attributes were each held at 10% (i.e. 10% of 44). The final result of the seven MAVT runs carried out (named according to the attribute weighting that was increased to 40%), and the standard result shown in Table 7, are shown in Figure 6.

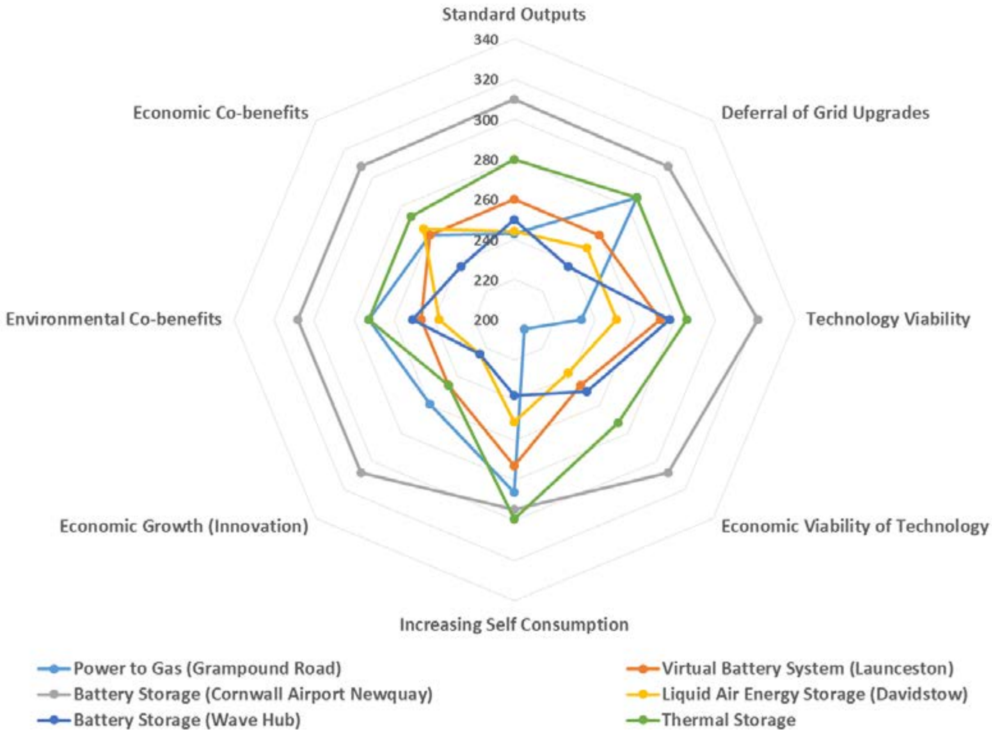


**Figure 6 Sensitivity analysis - weightings**

Figure 6 shows that the battery storage at CAN scores highest for almost every MAVT run undertaken. Even where increasing self-consumption is given the highest weighting, which is the attribute that the battery storage at CAN scores the lowest value on, this project still ranks second.

TES is the other project that consistently ranks highly; joint second or better except for where economic growth (innovation) is given the highest weighting. All the other projects tend to change their ranking as the attribute with the highest ranking is changed. From an assessment point of view this sensitivity analysis shows that even accounting for a relatively high level of subjectivity in the weightings battery storage at CAN and TES are found to provide the most benefit with a high level of confidence.

Aside from the attribute weightings, the partial value functions used are also subjective and so it important to assess the impact of changing these values as well. This was achieved by using a similar methodology as for the weightings, with the MAVT analysis again carried out seven times. This time on each MAVT run all partial value functions of one attribute were changed by an equal proportion so that the sum of this attributes partial functions represented 40% of the total sum of all partial value functions shown in Table 6 (i.e. 40% of 253). The sum of the partial functions for the other six attributes were held at 10% of the sum of all partial value functions. The final result of the seven MAVT runs carried out, named by the attribute which had its partial value functions increased by 40%, alongside the standard result are shown in Figure 7.

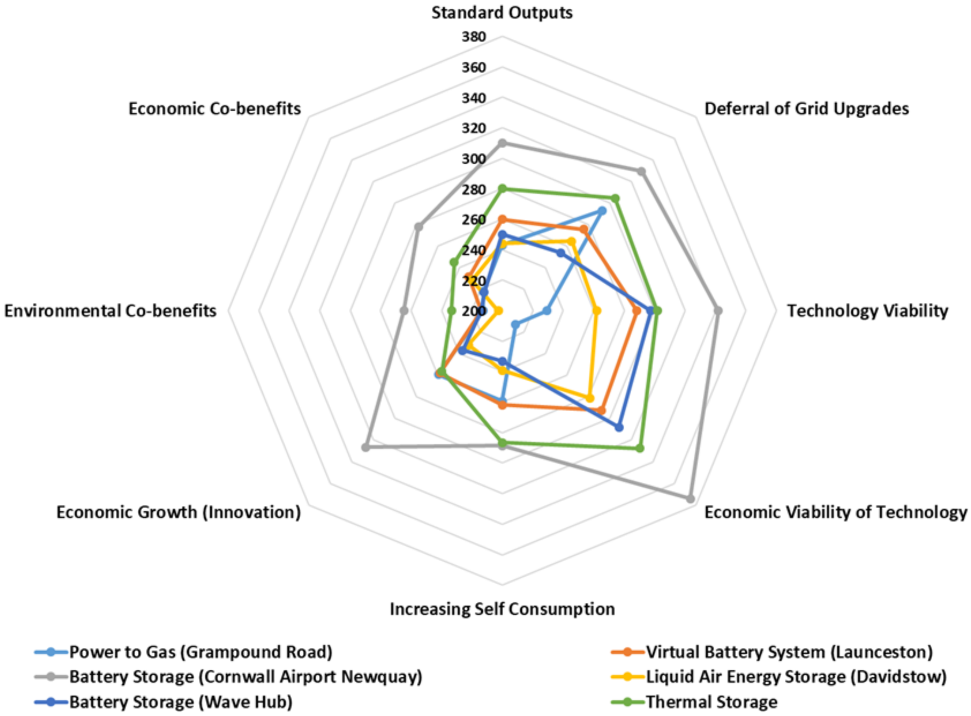


**Figure 7 Sensitivity analysis – partial value functions**

The results of Figure 7 are similar to those of Figure 6 but with some slight differences, for example; battery storage at CAN this times scores highest for every MAVT run including increasing-self consumption. While TES is still clearly the second highest scoring project on average it fares slightly less well on the economic growth run where it places fourth. Again there is slightly more variation in the other projects. This similarity in results between Figures 6 and 7 is not unexpected, the final scores of each project are linked to both the weightings and partial value functions, and so the impact of changing only one of these parameters, for only one attribute, is often limited.

The results of these sensitivity analyses suggest that in this instance the impact of individual subjectivity was limited. However, if the sensitivity analysis had shown a greater variation in the 'best' projects under each run then it may be necessary to undertake further analysis. This may take the form of more detailed feasibility analysis for specific project options to attempt to validate the partial value functions used but could also include more detailed sensitivity analysis.

One such sensitivity technique which is widely cited in the literature, for example by [84] and [85], as being applicable with MCDA approaches is Monte-Carlo simulations. Monte-Carlo simulations involve running many iterations of the MCDA with a parameter(s) (usually the weights, but it can be the partial value functions) randomly selected each time according to a probabilistic distribution. Monte Carlo simulations allow a wide range of possible outputs to be considered and measure the likelihood of a given set of outcomes occurring however, like any statistical technique they are dependent on their inputs particularly the type of probability distribution used and the upper and lower limits of this distribution [86]. Although using a normal distribution may provide a good starting point determining the upper and lower limits for the attributes assessed in this study is challenging; selecting the weighting for an attribute, even as an upper or lower limit is subjective. In the case of the partial value functions many of them are qualitative and do not have upper and lower limits which are readily available in databases and so the decision is again subjective. Given the challenge in determining these limits and the relatively insensitive nature of the results as shown by the analyses already carried out, it was decided that Monte Carlo simulations would not be undertaken as part of this paper. However, future work will consider the role they may play when using this framework.

# 4. Discussion

## 4.1 Strengths and Weaknesses of MAVT for Assessing ES Projects

As the need for ES grows an increasingly diverse body of decision makers, many of whom operate at a local level, including local authorities, community groups and private organisations will be required to assess ES options. These organisations play an important role in facilitating the transition to a sustainable energy system [19], however many have limited resources and/or technical expertise. Therefore, they require a decision-making approach which considers the multi-dimensional nature of energy storage options but is practical for use and easily accessible by a wide-range of decision makers and stakeholders. The MAVT framework presented here represents such an approach.

Indeed, one of the key strengths of MAVT is that it is simple and user friendly without the mathematical and computing complexity of alternatives [47], however at the same time the weighted nature of the attributes provides greater insight than a simple aggregated approach. The framework presented also helps to create a process for engaging with stakeholders which is helped by the fact that MAVT can be easily presented visually.

In practise, these strengths were found to be vital in the successful use of the framework. With only a brief introduction CC and a range of stakeholders, many with expertise only in one specific area, were able to understand, engage with and use the framework to consider ES options against factors covering a range of disciplines. This was due to the relatively simple method employed and the ease by which preliminary results could be presented. This allowed a consensus to be reached on the options to be progressed.

Away from its practical nature a further strength of MAVT is that additional options can be easily considered, as the attributes being considered do not change [87]. A final quality of MAVT, particularly relevant to ES, is how it can work with both quantitative and qualitative data [66, 88]. Our analysis used such a mix of attributes, for example input for the initial partial value functions used for economic viability were based on quantitative data from the reviewed literature (see section 2.4) in terms of cost and revenue. Whilst the environmental benefits were considered in more qualitative terms such as substantial or minor impact.

Despite these strengths MAVT does have some limitations; although it provides a structured methodology for informing decision-makers, much of the process is subjective [89]. This is discussed in section 2 including the trade-off between subjectivity and engagement with stakeholders. Section 3.4 discusses and demonstrates how MAVT allows subjectivity to be easily assessed using a sensitivity analysis, unlike for some techno-economic models where subjectivity is hidden [83].. The subjective nature of the process presents a risk to the replicability, and therefore reliability of the results as bringing together a different set of stakeholders with their own set of views may lead to a difference in inputs and the final result. This risk can be mitigated by selecting a wide range of stakeholders representing a broad range of views each time the analysis is carried out. Additionally, referring back to the sensitivity analysis, a small change in inputs had a minimal input on the final results suggesting that any variation of results should be within an acceptable level.

An alternative MAVT methodology would have been to individually interview each of the stakeholders to obtain their partial functions and attribute weightings and then produce a final averaged result. This may stop the view of more vocal, individual stakeholders dominating, but this has implications for the cost and time of the process. Furthermore, by defining partial value functions and attribute weightings in a group setting a consensus can be reached which takes into account the competing priorities of different stakeholders.

MAVT is designed to select the 'best' overall option considering all priorities and therefore it is important to select a wide range of stakeholders to reflect the range of priorities. Receiving feedback from a range of stakeholders and undertaking a sensitivity analysis can minimise subjectivity but will not entirely remove it. Therefore whilst MAVT can play an important role in helping to assess ES projects it should be used as part of a process and not as an isolated tool.

## 4.2 Insights from the use of MAVT

### 4.2.1 Local Priorities

The MAVT analysis undertaken in this paper highlights a number of important insights regarding the energy system around local priorities, timescales and co-location of ES, in ways which other methods may have not. Focusing first on local priorities, the results produced are heavily dependent not only on the partial value functions but also the attribute weightings. Whilst partial value functions may remain relatively constant for any given technology wherever it is located, attribute weightings will clearly change to reflect local priorities. For example, the high levels of congestion in Cornwall's grid network may have led to a higher weighting for 'Deferral of Grid Upgrades' than would have been obtained in other areas.

Furthermore, the attributes themselves may also change as priorities change from region to region. Some areas of Cornwall rank among the most deprived in the whole of the UK [90]; which may have contributed to 'Economic Growth (Innovation)' being identified as an attribute, whilst in other regions this may not be the case. Despite these changes in local priorities the UK's current energy system strategy is still largely a centralised top-down approach which does not consider localised issues [91]. Measures are beginning to address this such as local authority devolution deals which as in the case of CC can include an energy aspect, but local authority devolution deals are still relatively few and many either do not cover energy or only give minimal powers to local authorities [92]. The results in this paper highlight the need for decision makers to better account for the local diversity of national energy systems.

### 4.2.2 Timescales

The MAVT analysis carried out in this study was to assess ES options which could be developed in the near-term, as discussed in section 3.2 this resulted in less-mature technologies scoring low. This illustrates the need to periodically update the results of an MAVT analysis, and demonstrates the impact of timescale on decision-making in energy systems more generally.

The UK's energy policy can change rapidly and its future strategy is full of uncertainty [93], this may lead to significant policy changes as these uncertainties become known. In terms of an MAVT analysis, changes in energy policy could affect the importance of individual attributes used; for example more stringent environmental regulations may increase the importance of environmental benefits. There is also the risk that short-term priorities tend to be given more weight when decision making [94], meaning that ES options which provide longer-term benefits could be overlooked.

Whilst uncertainty over longer-term decision making cannot be fully mitigated it is essential that decision-makers and stakeholders are fully aware of the likely impact of timescale on the options they are evaluating, and continue to revise long-term strategies as technologies mature and uncertainties become known.

### 4.2.3 ES with Co-located Demand Centres and RET

The battery project at CAN received high partial value functions across all attributes leading to the highest total score, this was in part due to the ES opportunities provided by airports (section 3.2). However, it also provides an indication of the broader ES opportunities of co-locating large demand centres and RETs, particularly solar generation, with its large but inflexible generation peak during summer daylight hours. Deploying ES alongside co-located demand centres and RETs allows the power provided by the RET facility to be used by the demand centre as required, reducing congestion on the electricity network and lowering energy bills. Several studies have identified the potential for various forms of ES co-location with demand centres and RET, including at refrigerated warehouses [95], at university campuses [96], and as already discussed at airports [74]. However, to date there has been little in the form of policy to promote this as a market for ES.

## 5. Conclusion

With the increasing adoption of renewable energy technologies there is a growing need for energy storage, but energy storage technologies have different characteristics in terms of cost, performance and development. Furthermore, individual energy systems have their own specific technical, and non-technical needs, and are themselves part of a wider socio-technical system. Therefore, no single, or fixed combination, of energy storage technologies can be assumed for an individual case, so an approach is required which allows the benefit of specific energy storage technologies in specific energy systems to be assessed.

We find that multi-attribute value theory, a form of multi-criteria decision analysis, can form the basis of a straightforward and user-friendly process for assessing energy storage options; it enables decision makers to consider a range of technical and non-technical factors, allowing the options most suited to the needs of the local energy system and broader local priorities to be identified. This fills a gap for informing decision makers who often have limited expertise and resources (particularly at a local level), on which energy storage projects to support, with current available evidence based largely on techno-economic factors. Though there are limitations to the technique, performing an assessment based on multi-attribute value theory has also been found to be valuable by providing a structured framework for engaging stakeholders in the decision-making process.

This framework was demonstrated by assessing six potential energy storage projects in Cornwall. It found that a battery storage project at Cornwall Airport Newquay would provide the greatest overall benefits, with wide economic and environmental advantages. A thermal energy storage project was also found to provide significant value to the energy system, but scored lower on economic growth, in the context of an industrial strategy focused on battery technology.

Following on from the results produced Cornwall Council have taken the decision to develop a battery storage system at Cornwall Airport Newquay [97]. The fact that Cornwall Council have had the confidence in the result produced to invest in the project, particularly in the current climate of reduced local authority funding [98], provides support for the usefulness of the approach described in this paper. The framework presented in this paper provided additional value by revealing important insights for the development of energy systems, particularly the need to incorporate local priorities into decision-making to capture the full value of energy storage.

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## 7. Appendix A: Figure 1 and Figure 2 Methodology

For Figure 1; Cornwall's annual demand of 2,545GWh [1], was assumed to follow the same monthly profile as the UK as a whole [2]. The annual generation values in Table 1 of the main paper were broken down into monthly estimates according to monthly generation profiles taken from studies by Pfenninger and Staffell [3] for Solar PV and Sinden [4] for wind.

For Figure 2; Elexon, the UK's electricity balancing and settlement code company, produce standard load profiles for the daily pattern of electricity usage for eight types of customers across different periods of the year [5]. Profiles 1 and 2 which represent the majority of domestic and non-domestic customers respectively were used to disaggregate Cornwall's monthly demand, which according to the Department for Business, Energy and Industrial Strategy's sub-national electricity consumption data is split equally between domestic and non-domestic customers [1], into estimated hourly demands. The studies by Pfenninger and Staffell [3], and Sinden [4], also provide daily generation profiles and so these were again used, this time to disaggregate the monthly generation estimates to hourly estimates.

## 8. Appendix B: Energy Storage Projects

This section summarises the ES project options identified by the Masterplan, for more details see that document [6].

### 8.1 Power to Gas Grampound Road

This project is based on a 12MW electrolyser system which uses power to produce hydrogen gas by electrolysing water. It combines ES and an increase in electrical consumption by shifting heat demand to electrical demand to assist with balancing. The hydrogen produced can be stored and injected into the gas network to help meet thermal demand.

Grampound Road was selected as the location for this project as it has access to the gas network and is in the middle layer super output area[1] where electricity generation most exceeds demand in all of Cornwall.

Whilst this project could provide a balancing service by shifting heat demand and increasing electrical consumption it has the additional benefit of helping to retain more of Cornwall's 'energy capital' within the county and reducing congestion upstream in the network. However cost is a key barrier to this project [8], this is largely because the capital costs are high and the differential between the cost of electricity and the price of gas is not great enough to account for the efficiency losses of the energy conversion process.

### 8.2 Virtual Battery System North Cornwall

This virtual battery storage system revolves around the concept that a number of small storage systems (in this case batteries) normally in individual residences, can when required act as one large ES system. The benefits of this are flexibility as a varying number of batteries can be used at any one time, and a potential saving in cost compared to larger centralised battery storage systems [9]. Furthermore a number of households already have battery systems, often in conjunction with domestic PV systems which could be incorporated into the system. Lithium-ions batteries are typically used in domestic scale systems and so it is this technology which is assumed for this project.

The town of Launceston was selected for this system as it is a large population centre within an area where ES would be beneficial. Assuming a domestic lithium ion battery system of 2.5KWh and a 50% uptake would result in a virtual battery system of 10MWh.

Alongside flexibility additional benefits of this system include the fact that Lithium-ion batteries are relatively commercially mature (although the 'virtual' nature of the system is less so), and increased self-consumption as power produced from nearby renewables is stored and then consumed in Cornwall rather than transmitted across the grid out of the county. The barriers to this project are largely around the economic viability, although the costs of batteries is decreasing rapidly it is difficult to identify a valid revenue stream for this type of system although time of use tariffs and/or deferral of grid upgrades are two of the more promising options [10].

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[1] Middle layer super output areas are geographical areas with a population between 5,000 and 15,000, they are used for reporting statistics [7].

## 8.3 Battery Storage Cornwall Airport Newquay

Cornwall Airport Newquay (CAN), operated by Cornwall Airport Limited and owned by CC is a critical part of Cornwall's transport infrastructure and is the fastest growing regional airport in the UK [11]. In addition to CAN, CC also owns the Kernow Solar Park, a 5MW photovoltaic solar farm which lies adjacent to CAN and supplies a relatively small part of its electricity demand. This project is for a large-scale (5MWh) Lithium-ion battery; much of CAN's demand is during the evening/overnight whereas the solar park produces all of its electricity during the day, battery storage could be used to store some of the electricity generated to be used by CAN during the evening.

Benefits of this project include that it would free capacity on the distribution network as the solar park would predominantly be suppling CAN and it would make CAN less reliant on its back-up diesel generators. Additionally the economic viability of this project is likely to be high as CC own and operate both CAN and Kernow solar park so the electricity produced by the solar park can be purchased by CAN at a much lower rate than grid electricity presenting an obvious saving to CAN and/or an improved unit price for the solar farm.

Compared to the other projects considered here the main disadvantage of a battery storage system at CAN is that it does not increase self-consumption as much as some of the other projects; this is because the size of the ES scheme is smaller than others considered.

## 8.4 Liquid Air Energy Storage (LAES) Davidstow

This project comprises of a 15MWh Liquid Air Energy Storage (LAES) plant sometimes referred to as cryogenic storage [12], hosted at a refrigerated food processing facility in North Cornwall. North Cornwall was selected as it is an area where generation substantially exceeds demand and so would benefit from ES.

By hosting an LAES plant at a refrigerated food processing facility the cold energy produced by the LAES plant can be used to provide cooling to the facility allowing it to go 'off-grid' during times of peak demand. This not only increases the net efficiency of the LAES plant but also lowers the energy tariff of the host facility.

Compared to some of the other projects considered here the main disadvantage of an LAES plant is that economic growth to the wider community through innovation is likely to be relatively small. This is because LAES is still at the demonstrator stage so there is unlikely to be a large rollout of LAES plants in the short to medium term.

## 8.5 Battery Storage Wave Hub

The Wave Hub situated 10 miles off Hayle on the North Cornwall coast is the world's largest grid connected site for the testing of offshore renewable energy devices, particularly wave energy devices [13]. CC recently took ownership of the Wave Hub which forms part of the Hayle, Falmouth and Tolvaddon Marine Hub Enterprise Zone.

Although device specific the power generated by wave devices can fluctuate significantly; by 100% or more on a second by second basis due to the variation in wave amplitude and frequency [14]. Significant fluctuations in the level of supply onto the distribution network can seriously affect the voltage stability of the distribution network which traditionally is dealt with by physically upgrading the grid [10]. This project proposes using a 5MW Lithium-ion battery storage system to smooth the supply as an alternative way to stabilise the voltage to avoid grid upgrades.

Despite the reasoning for this project, grid upgrades are unlikely to be required due to the Wave Hub in the short to medium term as wave energy is still a developing sector so generation at the wave hub is likely to be relatively small. As with the other lithium-ion projects considered here one of the main advantages is the relative commercial maturity of the technology. Compared to other projects considered one of the main disadvantages of this project is the fact that it is unlikely to stimulate economic growth from innovation; whilst the Wave Hub itself might provide economic growth this ES project is unlikely to substantially contribute to this.

### 8.6 TES

Cornwall's housing stock is poor and much of Cornwall is not connected to the gas network, both of which contribute to levels of fuel poverty well above the national average [15]. TES can help provide affordable heating options and so as well as EES, has a role to play within Cornwall's energy system.

The project proposed is a seasonal pit TES system of up to 4,600MWh, which in conjunction with a solar thermal or other heat generating system such as geothermal could meet the winter thermal demand of around 1,500 homes. Unlike the other projects considered in this paper this project is not site specific but could be sited in any new development in Cornwall.

The main advantages of this project are that as a very large ES system it has the potential to significantly increase self-consumption and reduce the need for grid upgrades. This is because by allowing energy generated on site to be stored until it is required, less energy (either gas or electricity) will need to be imported on demand, so increasing self-consumption and reducing grid upgrades. An additional advantage of this system is that the technology has been demonstrated and so is relatively viable [16]. The main disadvantage of this technology is that there is relatively little scope for economic growth through innovation), as thermal storage technologies are a low priority for innovation funding in the UK [17] , additionally the economic viability of the project is not as good as some of the other projects considered.

## 9. Appendix A and B References

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